Section Report No. 331-2

PRELIMINARY INVESTIGATION OF OPTICAL COMMUNICATIONS WITH LASERS

Sidney Frankel

NOTICE

The attached publication is a Jet Propulsion Laboratory Section Report. Section Reports are not to be considered as official publications of the Jet Propulsion Laboratory. They are for the use of laboratory personnel only and are not to be released to outside agencies without specific authorization from the Reports Group and/or the Laboratory Director.

When writing official laboratory reports, authors are cautioned that Section Reports are not to be used for reference purposes.

JPL 80-034

CONTENTS

TABLES

FIGURES

I.   INTRODUCTION

Since stimulated electromagnetic emission in the visible region with a high degree of coherence has recently been demonstrated (Ref. 1-4), it has been suggested that this phenomenon might be applied to space communications. The short wavelengths associated with visible radiation appear to offer particular advantages in high antenna gains.

This report presents the results of a preliminary investigation of the use of Lasers[1] as sources and receiving amplifiers in a space-to-Earth communications link. A form of the range equation suited to the properties of the system components is derived, and some of the problems and limitations are discussed.

Figure 1 presents a block diagram showing the major components that might be associated with a space-to-Earth optical link. Except as noted otherwise, the purpose of the system in Fig. 1 is limited to furnishing a space-Earth signal for angle and doppler tracking. Incoherent light in the neighborhood of 0.5 micron from the stimulator (1) excites the Laser (2). The Laser output, practically monochromatic, is fed to the transmitting antenna (4), possibly through some sort of modulator (3). The signal, radiated to the receiving antenna (5) on Earth, is demodulated in some sort of detection system (6). We wish to determine, within this framework, an arrangement that yields maximum tracking range.

---

[1] Light amplification by stimulated emission of radiation.

II. ANALYSIS OF SYSTEM COMPONENTS

A. Characteristics of Laser Output

To illustrate typical Laser characteristics, the properties of a laboratory unit recently developed by Hughes Aircraft Company (Ref. 4) will be considered. This unit in its present form requires 30 kw of peak power to generate the needed pumping energy at 0.5 micron. The Laser output is 300 watts peak at 0.6943 micron (6943 $\overset{\circ}{A}$). This emission, only about 0.1 $\overset{\circ}{A}$ wide, is essentially monochromatic and is considered coherent. In terms more familiar to communications engineers, this represents a bandwidth of about 6 kmc (6×10^9 cps). The signal can be represented as narrow-band gaussian noise.

The energy emerges from the Laser through a circular orifice 1 cm in diameter. The measured beam width of the radiation is about 0.01 rad, much greater than predicted for a Fraunhofer diffraction pattern at that frequency.

For the immediate discussion the modulator will be ignored. The light from the Laser goes directly to the radiating system, the properties of which are governed by geometrical optics because of the extended size of the source. (This is discussed in more detail below.) On the other hand, because of the large distances between transmitter and receiver, the source appears as a point. Behavior of the receiving antenna is governed by the nature of the collector at the focus.

Because of the somewhat peculiar nature of the radiation, and because of the lack of receiving components at these wavelengths comparable to those available at ordinary radio frequencies, the detection system presents a special problem. This will be discussed subsequently.

Perhaps the first and most obvious question that can be asked concerns the Laser output: To what extent does the noisy nature of the signal reduce its usefulness?

Following Rice (Ref. 5) we can write for, say, the electric field component at any point

$$E = e_1 R \cos (\omega_m t + \theta) \tag{1}$$

$$e_1 I_n \tag{1a}$$

where

$\mathbf{e}_1$ = unit vector, a slowly varying function of time

R = the envelope of **E**, a slowly varying function of time

ω_m = midband angular frequency

t = time

θ = phase, a slowly varying function of time

$V_n = R \cos(\omega_m t + \theta)$

This signal, detected in, say, a square law device, yields an output current of the form

$$I = \alpha R^2 \left[\frac{1}{2} + \frac{1}{2} \cos(2\omega_m t + 2\theta) \right] \qquad (2)$$

where α is a transfer constant.

The current represented by I contains frequencies clustered around zero and $2\omega_m/2$. For this discussion the frequencies around zero are of interest. These are represented by the term $\alpha R^2/2$ in Eq. (2). Rice goes on to show that the square of the dc component, I_{dc}^2, and the mean-square low-frequency ac component, I_{lf}^2, are equal:

$$I_{dc}^2 = \overline{I_{lf}^2} = \alpha^2 \overline{V_n^2} \qquad (3)$$

Thus the dc power is equal to the total low-frequency ac noise power.

If a low-pass filter is used, the noise power is reduced. Rice shows further that the ac spectrum is approximately triangular, with the maximum at zero frequency, falling to zero at $f = \beta$, where β is the bandwidth of the original signal. Thus we can write for the ac spectrum

$$u(f) = k(\beta - f) \qquad (4)$$

where k is a constant to be determined. The total low-frequency ac power is

$$\overline{I^2}_{lf} = \int_0^\beta w(f)\, df = \frac{k\beta^2}{2} = I^2_{dc}$$

whence

$$k = \frac{2 I^2_{dc}}{\beta^2} \tag{5}$$

If a low-pass filter cutting off at f_c is used, the noise power is

$$N(f_c) = \int_0^{f_c} w(f)\, df = \frac{I^2_{dc}}{\beta^2}(2\beta f_c - f_c^2) \tag{6}$$

with the help of Eq. (4) and (5). The ratio of dc power to filtered noise power is then

$$\rho = \frac{I^2_{dc}}{N(f_c)} = \frac{\beta^2}{2\beta f_c - f_c^2} \tag{7}$$

For $f_c << \beta$, Eq. (7) tends to

$$\rho \approx \frac{\beta}{2 f_c} \tag{8}$$

Thus if $\beta = 6 \times 10^9$ cps and we take $f_c = 3 \times 10^4$ cps as a figure well in excess of present requirements, ρ is 10^5 or 50 db. If the amplitude of the signal is modulated slowly (less than 3×10^4 cps rate) we can expect to detect the modulation with little noise contributed by the carrier.

B.   Analysis of Transmitting Antenna Gain

If the Laser output port could be treated as a point source, a transmitting antenna with high gain based on the usual diffraction theory could be designed. Unfortunately, the fact is that, for reasonable focal distances, the

Laser output is far from a point source. The situation is typified in Fig. 2, where AA' is an optical axis coinciding with the axis of the output orifice O of the Laser. The diameter of this circular orifice is d, located at the focus of the parabolic dish at a distance F from the apex. The dashed line BCD represents one extreme ray from the source to the parabola apex and out. The line DCB represents the other extreme ray. Then it is clear from geometric optical considerations that the width of the beam leaving the parabola cannot be less than

$$\theta_d = \frac{d}{F} \tag{9}$$

and this will be the governing equation unless F is made sufficiently large. To see how far one has to go before this equation becomes questionable, consider a parabolic reflector 10 cm in diameter. The Fraunhofer diffraction beam width from such a reflector is approximately

$$\theta = 1.22 \frac{\lambda}{D} \tag{10}$$

and since we are using $\lambda = 0.7 \times 10^{-4}$ cm,

$$\theta = 1.22 \frac{0.7 \times 10^{-4}}{10} = 0.85 \times 10^{-5} \text{ rad}$$

Referring to Eq. (9), a focal length F yielding this same angle would be

$$F = \frac{d}{\theta_d} = \frac{1}{0.85 \times 10^{-5}} = 1.18 \times 10^5 \text{ cm}$$

or $F \simeq 1180$ meters.

Arrangements for obtaining such a large focal length appear impractical at the present time. It appears, therefore, that the gain of the transmitting antenna is governed by geometric optics principles rather than by Fraunhofer diffraction theory. In fact, if the power incident on the transmitting antenna is P_t, the radiated power incident per unit area within the main lobe at a distance r from the antenna is

$$P_i = \frac{4 P_t}{\pi \theta_d^2 r^2} = \frac{4 P_t F^2}{\pi d^2 r^2} \tag{11}$$

Incidentally, it is instructive to compute the gain of the transmitting antenna. This is given by

$$G_t = \frac{16}{\theta_d^2} = \frac{16 F^2}{d^2} \tag{12}$$

For example, for $d = 1$ cm and $F = 2$ meters,

$$G_t = \frac{16 \times 4 \times 10^4}{1} = 6.4 \times 10^5, \text{ or 58 db}$$

In subsequent discussions 58 db will be used as a reasonable figure.

The diameter of the transmitting reflector D is determined from the angle of spread θ_s:

$$D \approx F \theta_s = d \frac{\theta_s}{\theta_d} \tag{13}$$

For the example given, $D = 2$ cm, and the beam angle has been reduced by only a factor of 2.

C. Receiving Antenna Gain

If the receiver at the focus could be considered an optical point, the design of the receiving antenna would follow well-known antenna optical design principles, with practical limitations fairly well understood at JPL. (Ref. 6). Because of irregularities on the surface of a reflector, maximum theoretical gain is realized with greater and greater difficulty as the ratio of reflector diameter to wavelength is increased. For this reason we assume a 5-ft-diameter reflector as reasonable for the present application. Theoretically, under perfect conditions this reflector would have a gain of 137 db. By extrapolation from JPL experience at Goldstone, a gain of about 134 db might be expected for a point receiver.

Actually, the receiver is not a point; the gain obtained depends generally on the nature of the receiver.

If the receiver is a photocell, it will respond in proportion to the total light incident on the sensitive surface. Ignoring telescope losses, the amount of light is proportional to the collecting area of the telescope, provided the area of the photosensitive surface exceeds the cross section of the received light. This is easily true in the present instance. The collecting area of the telescope, translated into terms of gain, yields the previously mentioned figure of 134 db.

If a Laser preamplifier is used, with an entrance port of 1 cm, a gain the size of the focal spot will be much less than the area of the collector, and we have to assume the full gain of 134 db. What happens to the energy after it gets into the preamplifier cavity is another matter.

In subsequent discussions 134 db will be used as a reasonable figure.

The signal delivered at the output terminal of the receiving antenna is thus obtained with the help of Eq. (11):

$$P_r = P_i A_r = P_i \frac{G_r \lambda^2}{4\pi} = \frac{P_t F^2 G_r \lambda^2}{\pi^2 d^2 r^2} \tag{14}$$

$$= \frac{P_t G_t G_r \lambda^2}{16 \pi^2 r^2} \tag{14a}$$

by virtue of Eq. (12).

Substituting the previously determined values for G_t and G_r yields

$$P_r = \frac{P_t}{r^2} \times 10^5 \tag{15}$$

where r is in meters.

D. Detection

The problem of signal detection suggests several solutions for consideration: Laser preamplification, photoelectric detection, mixing and I.F. amplification (provided a suitable mixer can be found!). The first two

possibilities suffer from an inherent difficulty. The noise temperature is determined by the energy involved in a quantum transition:

$$E = h\nu = kT_e = \frac{hc}{\lambda} \tag{16}$$

or

$$T_e = \frac{hc}{k}$$

where T_e = effective noise temperature, $^\circ$K

h = Planck's constant = 6.625×10^{-34} joule-sec or watt-sec^2

c = velocity of light = 3×10^8 meters/sec

k = Boltzmann's constant = 1.38×10^{-23} joule/$^\circ$K or watt-sec/$^\circ$K

λ = 0.7×10^{-6} meter

whence, for the Laser or the photoelectric detector,

$$T_e = \frac{(6.625 \times 10^{-34})(3 \times 10^8)}{(1.38 \times 10^{-23})(0.69 \times 10^{-6})} = 20,000^\circ K$$

Compared to 300°K, this represents a noise figure of 18.3 db. Actually this figure is not nearly approached with either Lasers or photodetectors in the Laser band at 0.7 micron. The high losses due to moding in Lasers and the poor conversion efficiency in photocells in the red region raise this value considerably.

There is marked advantage in using a Laser preamplifier followed by a photoelectric detector. Although the resulting Rayleigh-distributed signal is suitable for angle tracking by virtue of the recoverable dc component, it is difficult to see how it could be used to recover doppler.

The superheterodyne approach suffers in addition from the fact that no suitable mixer is known, at least to the writer of this report.

In the next section the use of a high-frequency subcarrier to recover doppler information will be discussed. However, it is first desirable to complete the present discussion of noise power problems with a consideration of the ambient noise picked up from the sky in the vicinity of the spacecraft. In Section II-C, it was pointed out that in

the case of the photocell, and perhaps in the use of the Laser, the extended receiving area does not affect the antenna gain. However, it does affect the amount of ambient noise picked up from the surrounding sky. Some rough estimates based on incomplete data indicate that night sky will not contribute excessive noise compared with that from the detector, but that blue daylight sky will increase the noise level by about 40 db unless the receiving aperture is stopped down to about 0.1 mm. These numbers must be considered very approximate, yielding, at best, order-of-magnitude information (Ref. 8, 9).

Parenthetically, it is desirable to indicate at this point an interesting feature of the acquisition problem. An antenna with a gain of 134 db has a beam width of the order of 10^{-4} deg, presenting an extremely difficult acquisition problem. On the other hand, an antenna of, say, 5-meter focal length with a 1-cm-diameter receiver, such as a photocell or Laser, at the focus (for night-sky use) has an acquisition cone angle of

$$\theta_a = \frac{1}{5 \times 10^2} = 2 \times 10^{-3} \text{ rad} = 0.115 \text{ deg}$$

which is of a practical order of magnitude. Thus, it appears that under these circumstances there is no serious acquisition problem.

What analogous arrangement at microwave frequencies yields this attractive and apparently contradictory combination of high gain and broad acquisition angle? The answer is many horn feeds placed in the focal plane of a reflector, each feed loaded with a separate receiver. A simple example would be to load each of the horns of a four-horn monopulse system with a separate receiver, with no other interconnections among the horns.

1. Use of Subcarrier to Recover Doppler

In order to make the system suitable for doppler tracking, and to suggest possibilities for telemetering, it is desirable to consider the use of a subcarrier which might be used for doppler tracking. The transmitted power represented by the field of Eq. (1) may be written

$$P_t = R_p^2 \cos^2 (\omega_m t + \theta) \tag{17}$$

where R_p^2 is a slowly varying function of time. Assume now that this power is amplitude-modulated at angular frequency ω_a so that Eq. (17) is modified to

$$P_{t_a} = R_p^2 \cos^2 (\omega_m t + \theta) \left[\frac{1}{2} (1 + m \cos \omega_a t) \right] \tag{18}$$

where m is the degree of modulation ($0 < m \leq 1$). Furthermore, $0 << \omega_a << 2 \pi \beta << \omega_m$.

Assume (as in a photoelectric detector) that the output current is proportional to the low-frequency component of Eq. (18):

$$I_0 = a \left[lf \left(P_{t_a} \right) \right] = \frac{a R_p^2}{4} (1 + m \cos \omega_a t) \tag{19}$$

where we have now assumed the carrier noise components in any narrow band of interest to be negligible.

It is worth noting at this point that the subcarrier preserves doppler information. The amount of doppler shift obtained on the subcarrier is the same as though it were being transmitted independently.

2. *Photoelectric Detection*

In order to be as specific as possible we will assume a photoelectric detector shielded somehow from all signals except those incident from the Laser transmitter. The incident power is of the form

$$P_{r_a} = \frac{R_p^2}{2} \cos^2 (\omega_m t + \theta) [1 + m \cos \omega_a t] \tag{20}$$

from Eq. (14a), and the spectrum of R_p is contained in a band β. Then Eq. (19) applies for the output current of the detector. In addition, the detector puts out noise current given by (Ref. 7)

$$\overline{I_n^2} = 2 e \overline{I_0} B \tag{21}$$

where

$\overline{I_n^2}$ = mean-square noise current, amp^2

e = charge on electron = 1.6×10^{-19} coulomb

I_0 = average emission current, amp

B = output circuit bandwidth, cps

Substituting for e,

$$\overline{I_n^2} = 3.2 \times 10^{-19} \, \overline{I_0} \, B \tag{22}$$

The following discussion is patterned after a similar one in Ref. 7. From Eq. (19),

$$\overline{I_0} = \frac{\alpha \overline{R_p^2}}{4}$$

whence in Eq. (22),

$$\overline{I_n^2} = 0.8 \times 10^{-19} \, \alpha \overline{R_p^2} \, B \tag{23}$$

The received power is given by Eq. (20), where the part representing the recovered modulation after detection by the photocell is

$$\left(P_{r_a}\right)_{lf} = \frac{\overline{R_p^2}}{4} \, (1 + m \cos \omega_a t)$$

The desired component, at angular frequency ω_a, is

$$\left(P_{r_a}\right)_{\omega_a} = \frac{\overline{R_p^2}}{4} \, m \cos \omega_a t$$

Then the signal current from the photo detector is

$$I_s = \frac{\alpha m}{4} \, \overline{R_p^2} \cos \omega_a t$$

whence

$$I_s^2 = \frac{a^2 m^2}{16} \overline{R_p^2}^2 \cos^2 \omega_a t$$

(24)

$$\overline{I_s^2} = \frac{a^2 m^2}{32} \overline{R_p^2}^2$$

The signal power—noise power ratio is, then, from Eq. (23) and (24),

$$\rho = \frac{\overline{I_s^2}}{\overline{I_n^2}} = \frac{a \overline{R_p^2} m^2}{25.6 \times 10^{-19} B}$$

(25)

Now if the power generated in the spacecraft were not modulated, the received power averaged over the carrier cycle would be $R_p^2/2$. But $R_p^2 = 2 \overline{R_p^2}$, or $\overline{R_p^2} = R_p^2/2 = \overline{P_r}$, where $\overline{P_r}$ is the received power in the absence of absorption modulation. If P_t similarly represents the transmitted power in the absence of absorption modulation, then, by Eq. (14a) and (25),

$$\overline{P_r} = \frac{\overline{P_t} G_t G_r \lambda^2}{16^2 r^2} = \overline{R_p^2} = \frac{25.6 \times 10^{-19} \rho B}{a m^2}$$

Then

$$r^2 = \frac{P_t G_t G_r \lambda^2}{16 \pi^2} \frac{a m^2}{25.6 \times 10^{-19} \rho B}$$

$$r = 5 \times 10^7 \left(\frac{\overline{P_t} G_t G_r \lambda^2 a m^2}{\rho B} \right)^{\frac{1}{2}} \text{meters} = 3.1 \times 10^4 \left(\frac{\overline{P_t} G_t G_r \lambda^2 a m^2}{\rho B} \right)^{\frac{1}{2}} \text{miles}$$

(26)

We have already determined that

$$G_t = 6.4 \times 10^5$$

$$G_r = 2.5 \times 10^{13}$$

$$\lambda^2 = 0.48 \times 10^{-12} \text{ meter}^2$$

From the RCA Type 917 phototube take $\alpha = 1.44 \times 10^{-3}$ μa/μw at 6943 Å. Also take $m = 1$, $B = 20$ cps, and $\rho = 10$. These figures yield

$$r = 2.31 \times 10^5 \ \overline{(P_t)}^{\frac{1}{2}} \text{ miles} \tag{26a}$$

In the tabulation below, r is calculated for various values of $\overline{P}_t$:

$\overline{P}_t$, watts	r, miles $\times 10^{-6}$
1	0.231
10	0.732
100	2.310
1000	7.320

3. *Detection Using Laser Preamplifier*

Can better results be obtained using a Laser preamplifier ahead of the detector? The noise power generated by the Laser is

$$P_n = \frac{hc}{\lambda} \ B \ N_L \tag{27}$$

where N_L is a factor introduced to allow for deterioration due to moding and other causes. Thus,

$$\rho = \frac{\overline{P}_r}{P_n} = \frac{\overline{P}_t \, G_t \, G_r \, \lambda^2}{16 \, \pi^2 \, r^2} \quad \frac{\lambda}{hc \, B \, N_L} = \frac{P_t \, G_t \, G_r \, \lambda^3}{r^2 \, B \, N_L \, \rho} \, 3.18 \times 10^{22} \tag{28}$$

$$r = 1.11 \times 10^8 \left(\frac{P_t \, G_t \, G_r \, \lambda^3}{B \, N_L \, \rho} \right)^{\frac{1}{2}} \text{ miles} \tag{29}$$

Substituting previously used values results in

$$r = 1.11 \times 10^8 \left[\frac{\overline{P}_t \, (6.4 \times 10^5) \, (2.5 \times 10^{13}) \, (0.7 \times 10^{-6})^3}{20 \times 10 \, N_L} \right]^{\frac{1}{2}} = 1.84 \times 10^7 \, \frac{(\overline{P}_t)^{\frac{1}{2}}}{N_L} \text{ miles} \tag{30}$$

If N_L is no worse than 100 (20 db),

$$r = 1.84 \times 10^6 \, (\overline{P}_t)^{\frac{1}{2}} \tag{30a}$$

an order of magnitude improvement over Eq. (26a) for direct photocell detection.

Laser researchers believe that N_L can be reduced to 10 in the next five years. Substituting $N_L = 10$ in Eq. (30) yields

$$r = 5.83 \times 10^6 \, (\overline{P}_t)^{\frac{1}{2}} \tag{30b}$$

The table below shows r tabulated for various values of $\overline{P}_t$ calculated from Eq. (30b).

$\overline{P}_t$, watts	r, miles $\times 10^{-6}$
1	5.83
10	18.4
100	58.3
1000	184

It must be emphasized, however, that while ultimate success may be expected in the development of a Laser preamplifier, this has not been accomplished to date, and many difficult (but presumably solvable) problems lie ahead.

III.   DETECTION RANGE, MICROWAVE SYSTEM VS LIGHT SYSTEM

At this point a comparable calculation of range based on use of a microwave carrier is appropriate. Assume the following conditions: operation at 2300 mc, a 250-ft parabola on Earth, and a 32-ft parabola in the spacecraft. Then

$$A_t = 60 \text{ meter}^2 \text{(effective)}$$

$$G_r = 2 \times 10^6$$

and assuming the use of a Maser receiver with a noise temperature of $100°$ K, and a received signal – noise ratio of 10, we get

$$r = 3200 \ (\overline{P}_t)^{\frac{1}{2}} \text{ miles} \times 10^6 \tag{31}$$

In Table 1 a comparison is made of the expected ranges for a microwave system and the most effective Laser systems discussed in this report.

Table 1.   Comparison of relative expected ranges

$\overline{P}_t$, watts	r, miles $\times 10^{-6}$	
	Radio	Light
1	3,200	5.8
10	10,100	18.4
100	32,000	58
1000	101,000	184

Equations (30b) and (31) indicate a factor of 550, or 55 db, in favor of the microwave system if the same transmitted power is assumed in both cases. Table 2 shows how this value is comprised of the various factors entering the range equation.

Table 2.   Factors governing relative expected ranges

Range equation factor	Microwave, db	Light, db	Difference between systems
G_t	45.0	58.1	– 13.1
G_r	63.0	134.0	– 71.0
λ^2 (referred to light)	106.0	0.0	+ 106.0
T_e (referred to 300°K)	4.7	– 28.3	+ 33.0
Total	218.7	163.8	+ 55.1

IV. CONCLUSIONS

In the foregoing analysis a fairly optimistic attitude has been taken concerning the rate of progress in the development of Laser techniques in the next one-to-five years. Nevertheless, it must be concluded that for equal transmitted power the microwave system is superior to the Laser system. In fact, in order to equal the microwave system in performance, Laser transmitted power must be of the order of 55 db greater than the required microwave power.

At the present state of development Laser operation is about 1% efficient as far as power consumption is concerned. The over-all efficiency of a microwave system is at least an order of magnitude better, thus exaggerating further the discrepancy in favor of the microwave system.

But the Laser system cannot be discarded until a few other questions are answered. First, can Laser efficiency be improved? Workers in the field believe they can attain 10% efficiency in the near future without too much difficulty. Can sunlight be used as the pump source? Preliminary investigation indicates that the use of sunlight may be marginal (Ref. 4); this merits a very careful look. But, at the same time, a Laser system using the sun as a power source should be compared with an optical system that uses the sun directly. Photocells designed to respond to sunlight have noise figures approaching theoretical within a few db, actually better than the hoped for figure of 28 db quoted for the Laser in Table 2. Although the Laser is much more coherent than sunlight, it appears to be incoherent enough to require a technical approach that classes it with sunlight rather than with a crystal oscillator, as far as communications applications are concerned.

The preceding analysis shows that at the present state of the art the transmitting antenna gain is limited by the finite size of the Laser output port. If this port can be made smaller, or if the angle of the radiation from it can be made of the order predicted by diffraction optics, then larger antenna gains for reasonable focal distances may be realized. Under these circumstances it should not be too difficult to build a spacecraft antenna with a gain of 110 db at light frequencies. This would represent an improvement of 52 db over the value given in Table 2. This, in turn, would reduce the gap between the two systems to 3 db, surely within the accuracy of this analysis. However, to accomplish this result the Laser must be capable of being designed to appear as a point source at reasonable focal distances.

Because of the extremely narrow antenna beam widths associated with light frequencies, acquisition of the spacecraft from the Earth could be a very difficult problem. One method of alleviating this problem is suggested. Although the antenna has a very narrow beam width, it can be designed to have a large field of view. An extended detector system (with a multiplicity of outputs, either parallel or sequential) could be placed in the focal plane of the reflector, the reflector pointed approximately to the right direction, and the signal detected by integration. The photographic plate is, of course, an example of such a detector, although perhaps not suitable for this immediate problem.

In conclusion, it must be pointed out that the Earth's atmospheric conditions frequently result in unacceptable attenuation to electromagnetic waves in the visible region. In any comparison of the relative merits of systems this must eventually be taken into account.

V. RECOMMENDATIONS FOR FURTHER STUDY

From the foregoing discussion some areas for subsequent investigation may be logically inferred. Among those subjects that merit study are the following:

1. Improved Laser power sources, and in particular, the feasibility of using sunlight as such a source.

2. The relative merits of Laser systems and direct-sunlight systems.

3. Methods of reducing cone angle of radiation from Laser and/or reducing its apparent size as a light source.

4. Acquisition methods with extremely narrow beam telescopes.

5. Methods of modulating the Laser output with frequencies in the tens of megacycles.

6. Low-loss methods of realizing a long focal length within a compact volume.

NOMENCLATURE

A_r	effective area of receiving antenna
A_t	effective area of transmitting antenna
B	output circuit bandwidth
c	velocity of light
D	diameter of transmitting reflector
e	charge on electron
e_1	unit vector
E	energy
$\mathbf{E}$	electric field
f_c	cut-off frequency
F	focal length
G_r	gain of receiving antenna
G_t	gain of transmitting antenna
h	Planck's constant
i_n	noise current
i_o	output current
i_s	signal current
I	output current
I_{dc}	dc component of current
I_{lf}	low-frequency ac component of current
k	Boltzmann's constant
m	degree of modulation
N_L	noise factor
P_i	incident power per unit area

NOMENCLATURE (Cont'd)

P_n noise power

P_r received power

P_{r_a} amplitude-modulated received power

P_t power incident on transmitting antenna

P_{t_a} amplitude-modulated transmitted power

r range

R the envelope of **E**

R_p amplitude envelope of transmitted signal

t time

T_e effective noise temperature

$V_n = R \cos (\omega_m t + \theta)$

$w(f)$ ac spectrum

α transfer constant

δ bandwidth of original signal

θ phase

θ_a acquisition cone angle

θ_d beam angle from transmitting antenna

θ_s beam angle from Laser

λ wavelength

ν frequency

ρ ratio of signal power to noise power

ω_a angular frequency

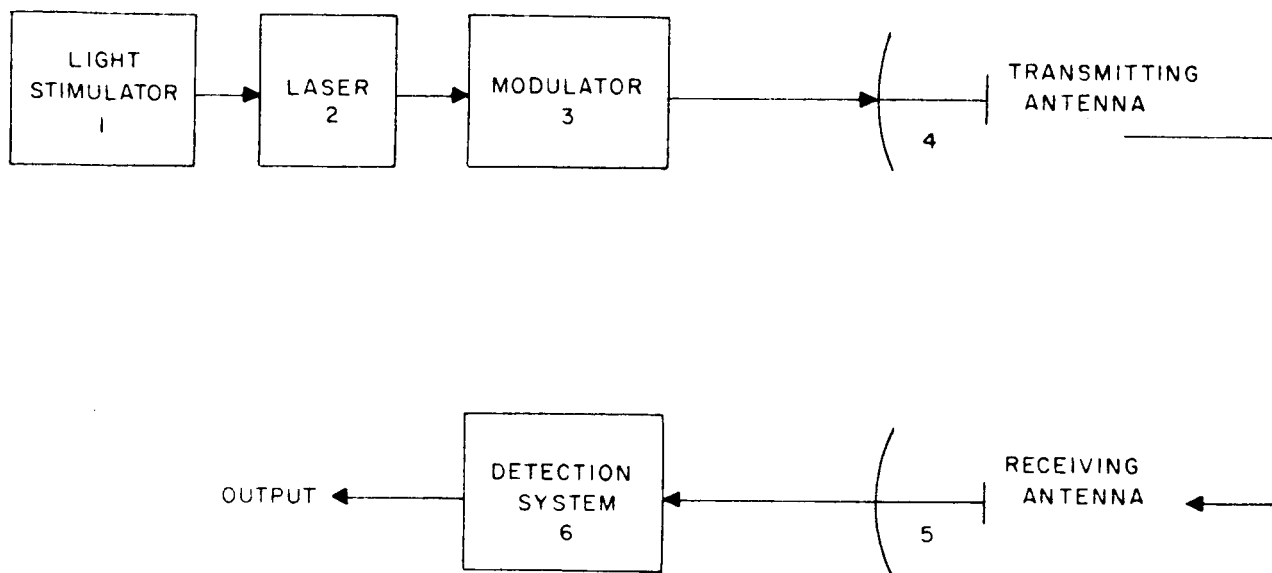ω_m midband angular frequency
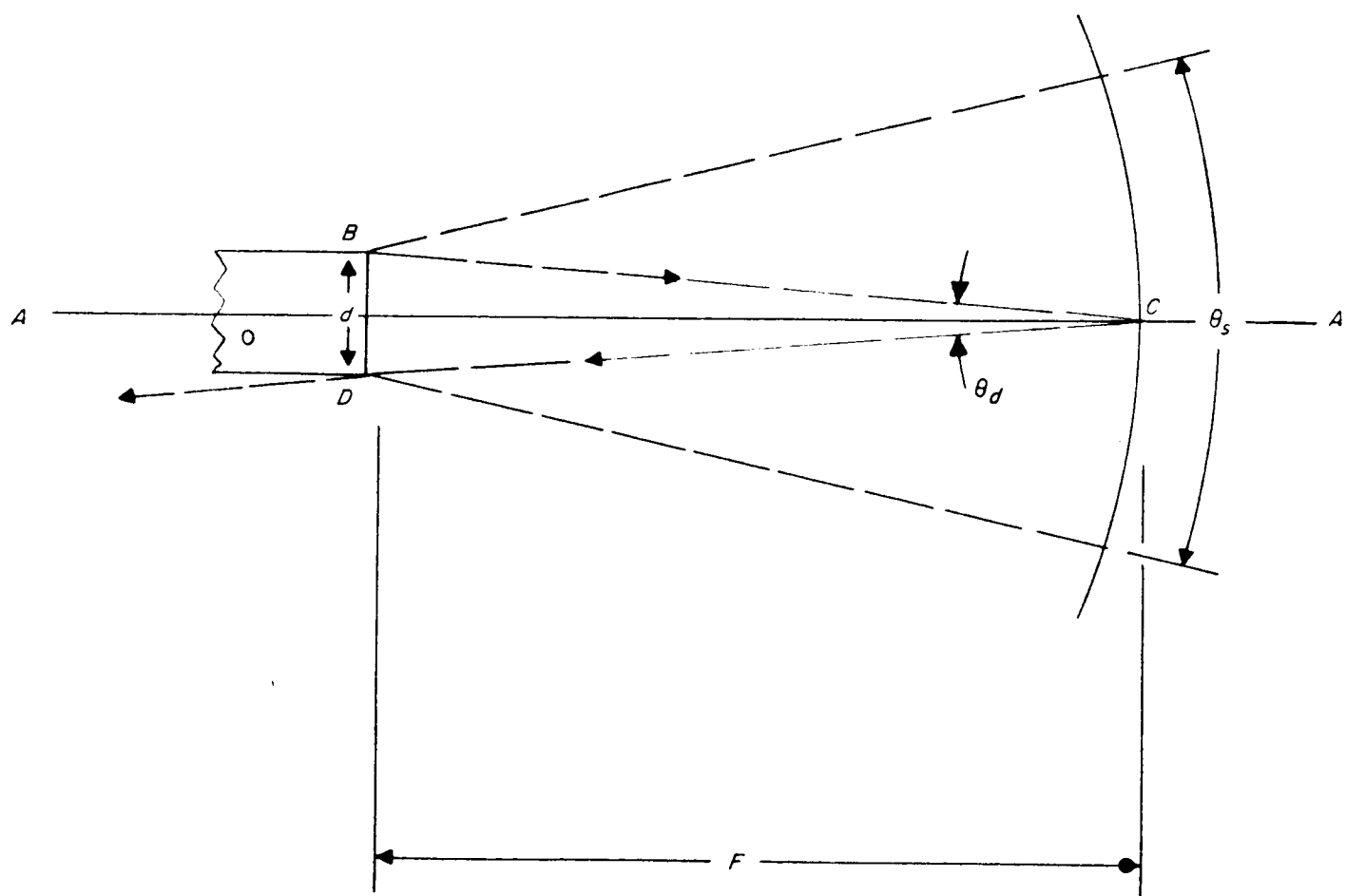
Fig. 1. Optical communications link (one-way)

Fig. 2. Transmitting antenna optics

REFERENCES

1. Schawlow, A. L. and Townes, C. H., "Infra Red and Optical Masers," *Physical Review,* 112(12):1940-1949, December 15, 1958.

2. Maiman, T. H., "Optical and Microwave-Optical Experiments in Ruby," *Physical Review* Letter, June 1, 1960.

3. Maiman, T. H., *Optical Maser Action in Ruby,* Hughes Research Laboratories, unpublished report.

4. *Laser Development at Hughes Research Laboratories,* Internal Report No. 331-336, Jet Propulsion Laboratory, September 9, 1960.

5. Wax, N. (editor), *Selected Papers on Noise and Stochastic Processes,* Dover, New York, 1954.

6. Rechtin, E., Stevens, R., and Victor, W. K., *Data Transmission and Communications,* Technical Release No. 34-55, Jet Propulsion Laboratory, Pasadena, April 30, 1960.

7. Zworykin, V. K., and Morton, G. A., *Television,* Chapter 1, Section 1.6, John Wiley and Sons, New York, 2nd Edition, 1954.

8. Allen, C. W., *Astrophysical Quantities,* Chapter 12, Athlone Press, University of London, 1955.

9. Hardy, A. C. and Perrin, F. H., *The Principles of Optics,* Chapter 9, McGraw-Hill, New York, 1932.